

NOVEL HEAVY QUARK PHYSICS PHENOMENA



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in collaboration with

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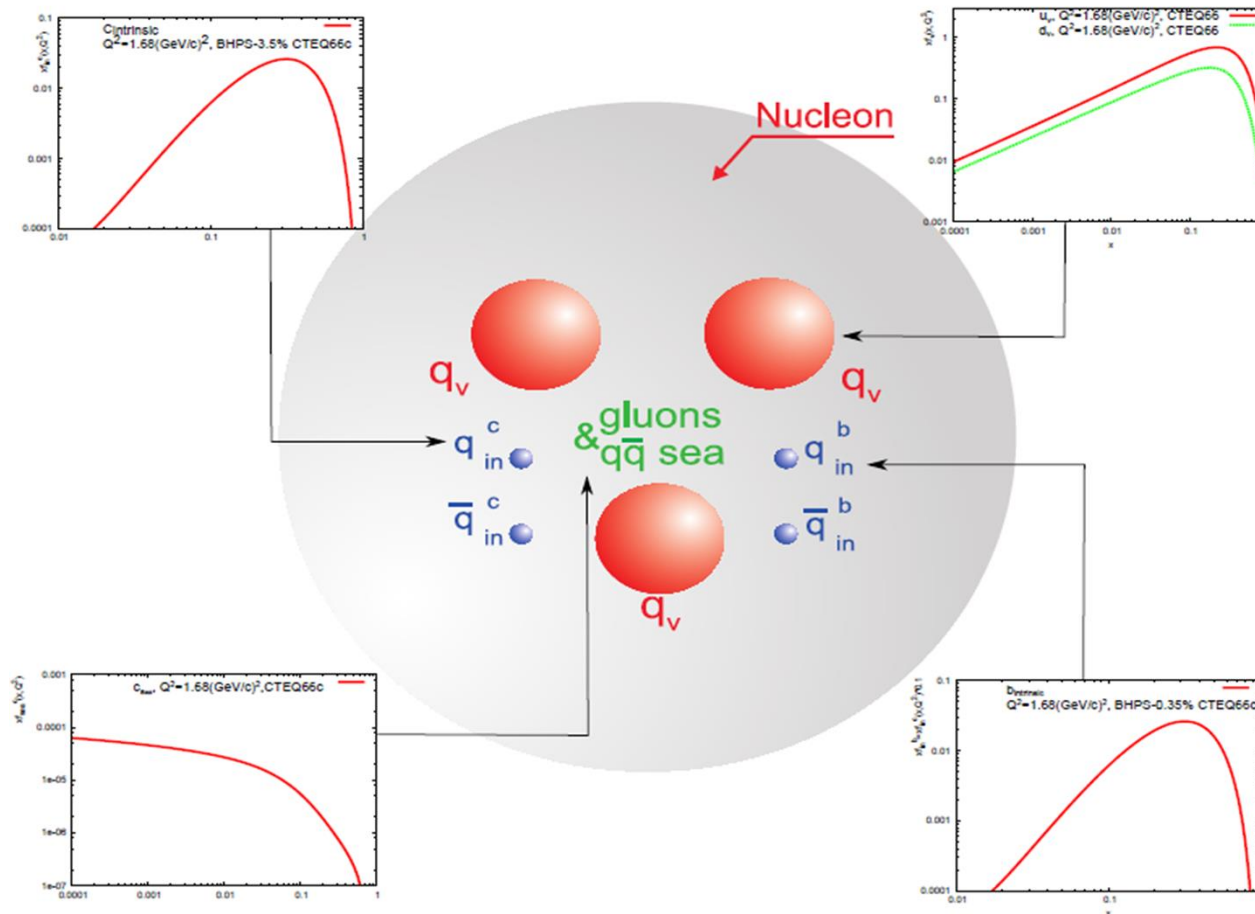


OUTLINE

1. Short overview of search for the **IQ** content in the proton.
2. Main goal of our study: searching for the **IC** signal in hard γ or Z-boson production accompanied by c-jet.
3. Extreme kinematics to observe **IC** signal in p_T -spectrum of Z or c-jet in $p+p \rightarrow Z+c+X$ processes.
4. Evidence for the **IC**, according to NNPDF fit and latest LHCb data on Z+c-jet production in pp.
5. Asymmetric charm-anticharm sea in a nucleon.
6. Summary.

BHPS model: S.J. Brodsky, P. Hoyer, C. Peterson and N. Sakai, Phys.Lett.B9(1980) 451; S.J. Brodsky, S.J. Peterson and N. Sakai, Phys.Rev. D23 (1981) 2745.

Intrinsic $Q\bar{Q}$ in proton



INTRINSIC HEAVY QUARK STATES

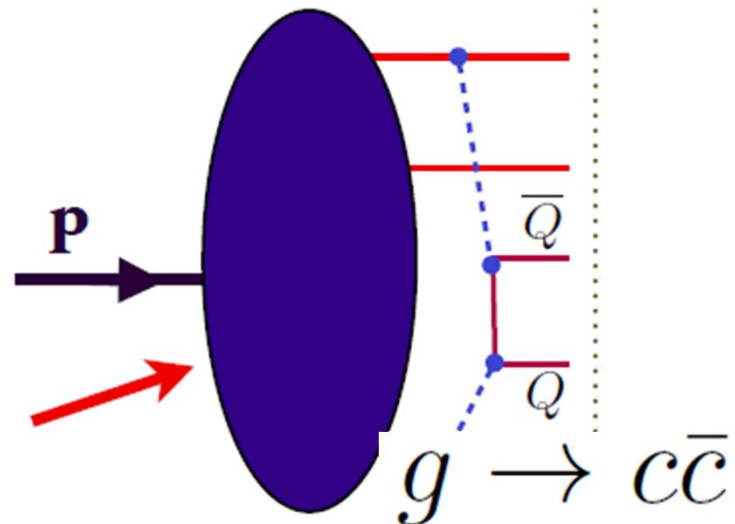
Two types of parton contributions

The extrinsic quarks and gluons are generated on a short time scale in association with a large transverse-momentum reaction.

The intrinsic quarks and gluons exist over a time scale independent of any probe momentum, they are associated with the bound state hadron dynamics.

$$P(x_1, \dots, x_5) = N_5 \delta\left(1 - \sum_{i=1}^5 x_i\right) \left[M_p^2 - \sum_{i=1}^5 \frac{m_i^2}{x_i} \right]^2$$

Proton 5-quark Fock State:
Intrinsic Heavy Quarks



*QCD predicts
 Intrinsic
 Heavy Quarks
 at high x!*

Minimal off-shellness!

$$x_Q \propto (m_Q^2 + k_{\perp}^2)^{1/2}$$

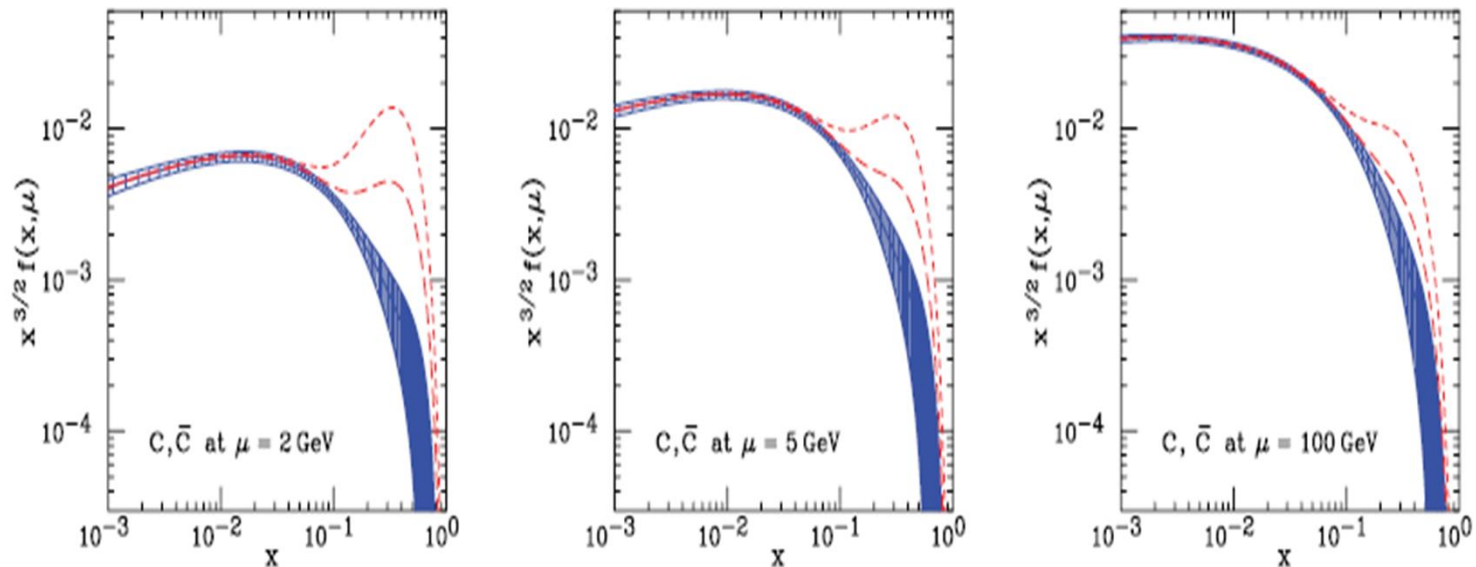
Probability (QED) $\propto \frac{1}{M_{\ell}^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

**Hoyer, Peterson, Sakai, Collins, Ellis, Gunion, Mueller, sjb
 Polyakov, et al.**

Lowest order DGLAP extrinsic contribution to $c(x)$ comes from the gluon splitting $g \rightarrow c\bar{c}$, which dominates at low x .

CHARM QUARK DISTRIBUTIONS IN PROTON



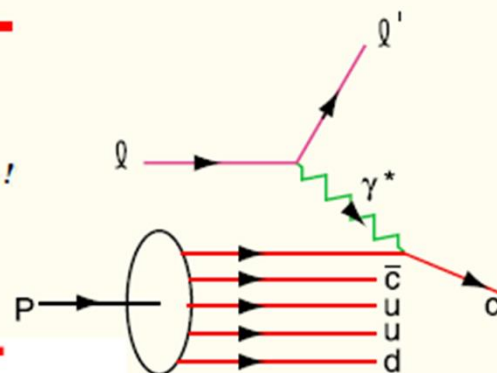
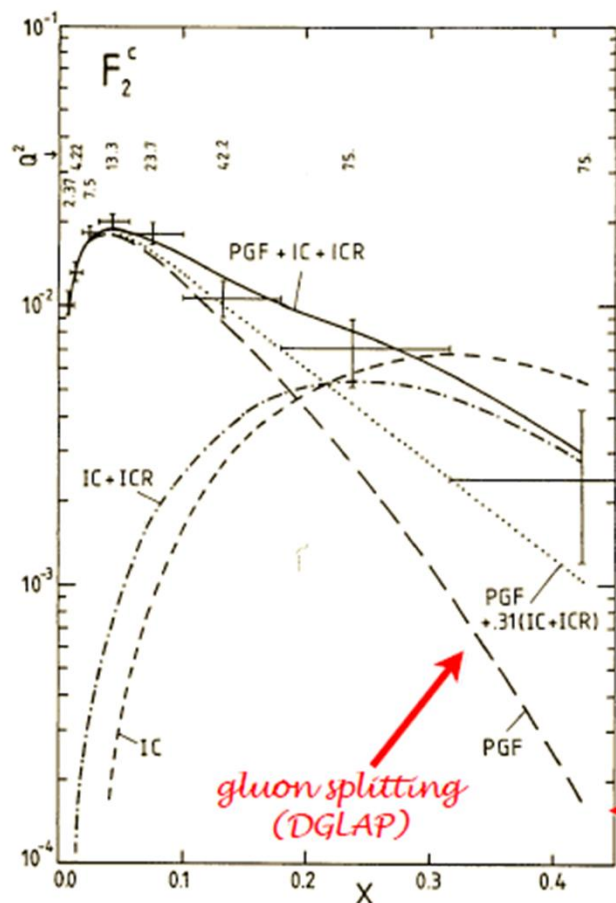
Charm quark distributions within the BHPS model. The three panels correspond to the renormalization scales $\mu = 2, 5, 100 \text{ GeV}$ respectively. The long-dashed and the short-dashed curves correspond to $x_{cc} = (0.57-2.)\%$ respectively using the PDF CTEQ66c. The solid curve and shaded region show the central value and uncertainty from CTEQ6.5, which contains no *IC*.

There is an enhancement at $x > 0.1$ due to the IC contribution

Measurement of Charm Structure Function

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-GeV Mu⁺ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

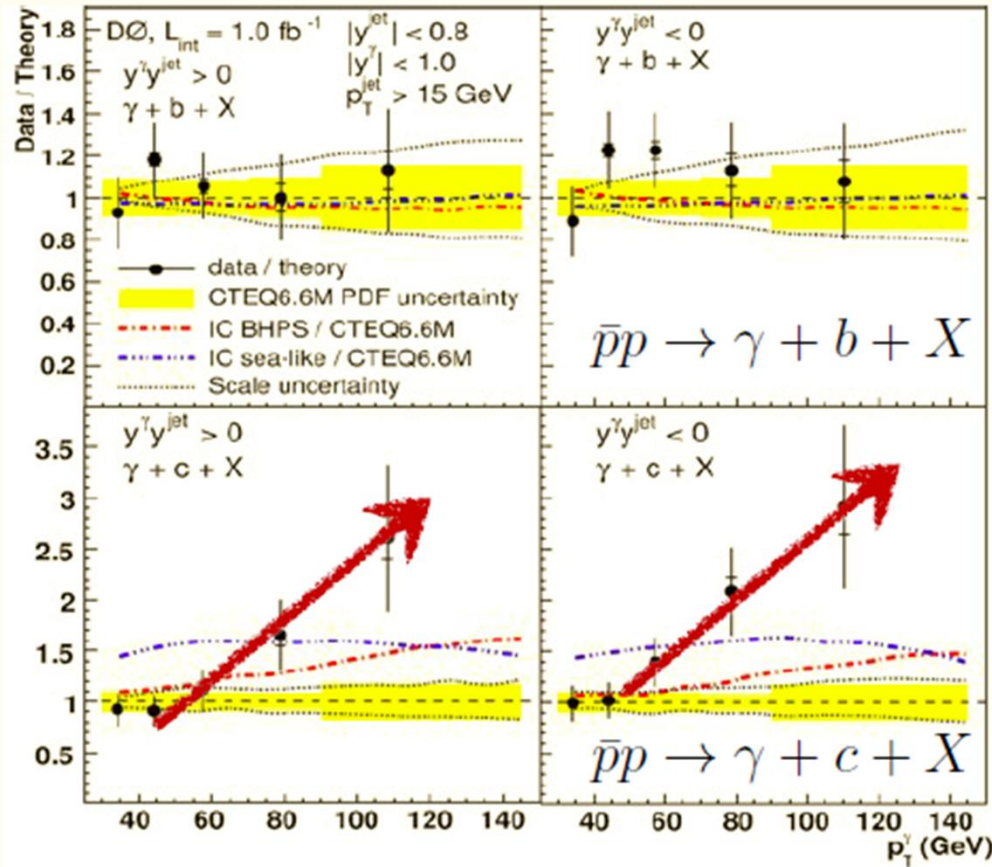
First Evidence for Intrinsic Charm



DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

D0Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections
in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

$$p\bar{p} \rightarrow \gamma + Q + X$$

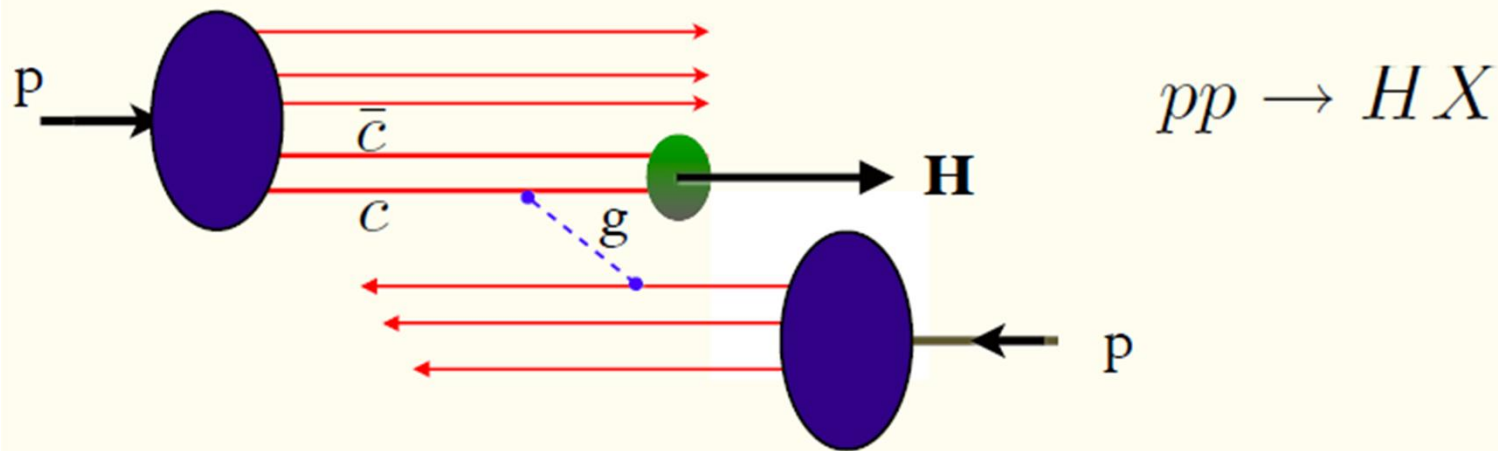
$$\frac{\Delta\sigma(\bar{p}p \rightarrow \gamma c X)}{\Delta\sigma(\bar{p}p \rightarrow \gamma b X)}$$

**Ratio is insensitive
to gluon PDF,
scales**

Consistent with $\frac{m_c^2}{m_b^2}$
relative suppression
of intrinsic bottom

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

*Intrinsic Charm Mechanism for Inclusive
High- X_F Higgs Production*



**Goldhaber, Kopeliovich,
Schmidt, sjb**

Also: intrinsic bottom, top

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

Higgs production is equal from the IC and IB

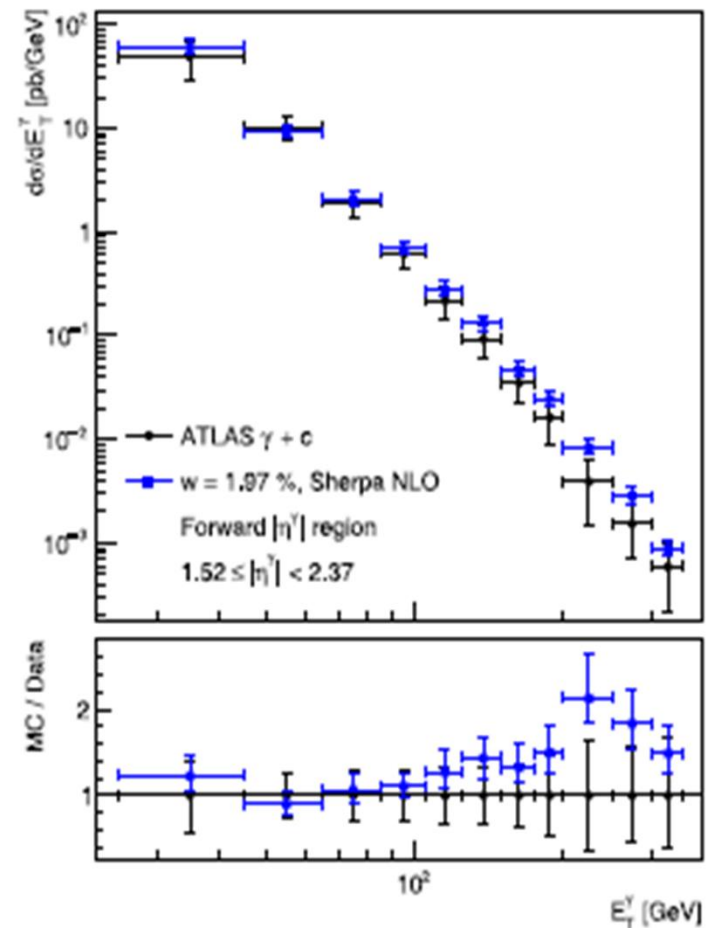
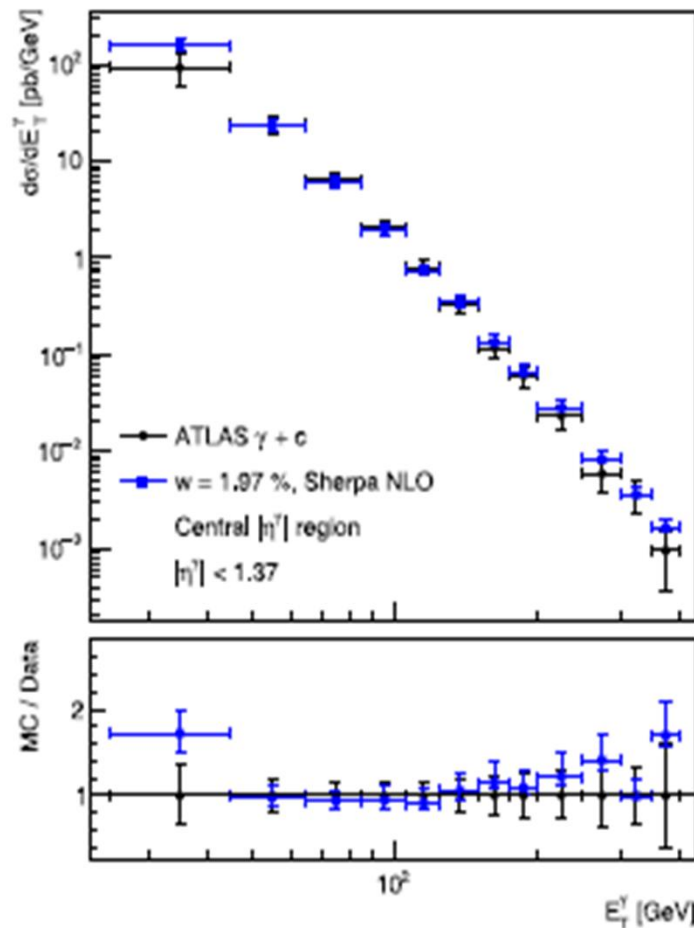
$p+p \rightarrow \gamma+c\text{-jet}+X$ at $s^{1/2} = 8$ TeV, ATLAS data

the upper limit of the **IC** probability is about 1.97%

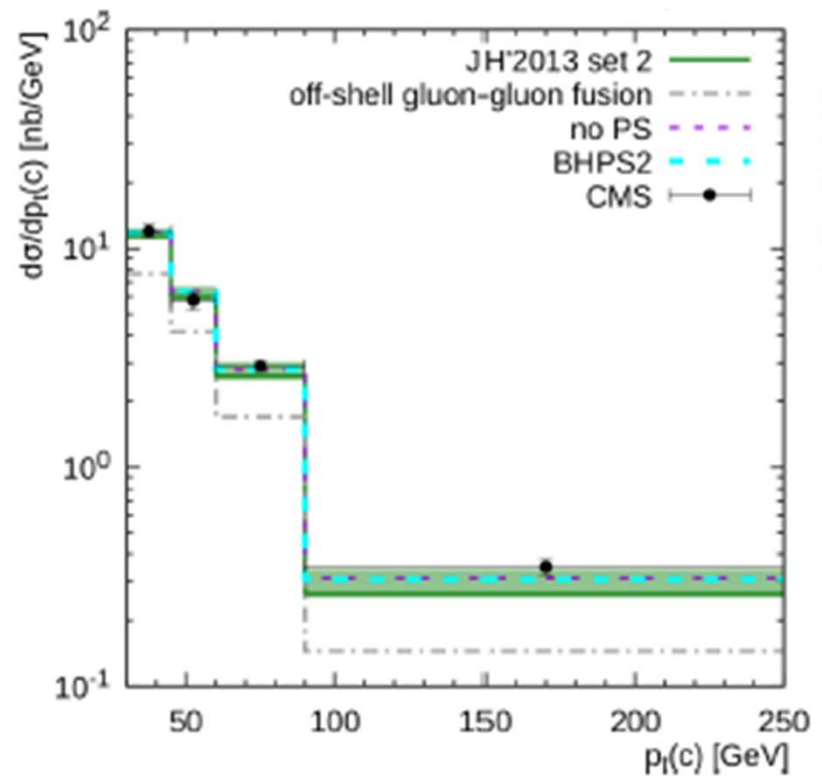
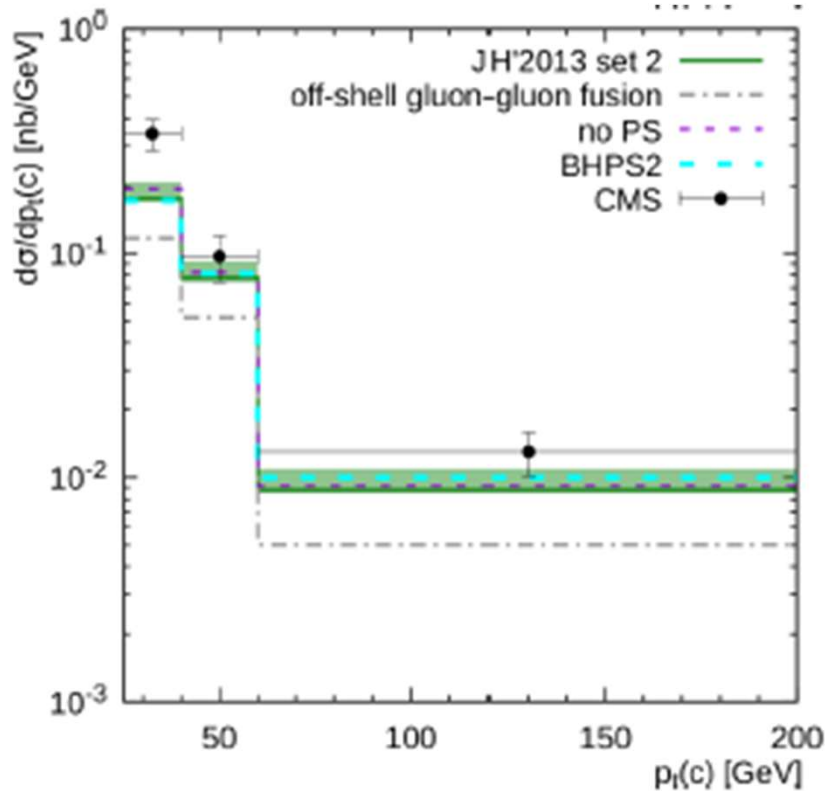
V.A. Bednyakov, S. J. Brodskiy, A.V. Lipatov, G.L., M.A. Malyshev, J. Smiesko,
S. Tokar, *Eur. Phys.J. C* 79, 92 (2019)

S.J. Brodsky, G.I. Lykasov, A.V. Lipatov et al. / Progress in Particle and Nuclear Physics 114 (2020) 103802

23



**$p+p \rightarrow Z+c\text{-jet}+X$ at $s^{1/2} = 8 \text{ TeV} \ \& \ 13 \text{ TeV}$
CMS data**



Left: the c -jet distribution as a function of its transverse momentum p_t^c at $s^{1/2} = 8 \text{ TeV}$; PS means the parton shower; BHPS2 corresponds to the IC probability about 3,5%

Right: the same as at left but at $s^{1/2} = 13 \text{ TeV}$.

A.V. Lipatov, G.I., M.A. Malyshev, S.M. Turchikhin, Phys.Rev. D 106, 054017 (2022)

$p+p \rightarrow Z+c/b\text{-jet}+X$ at $s^{1/2} = 13$ TeV
CMS data

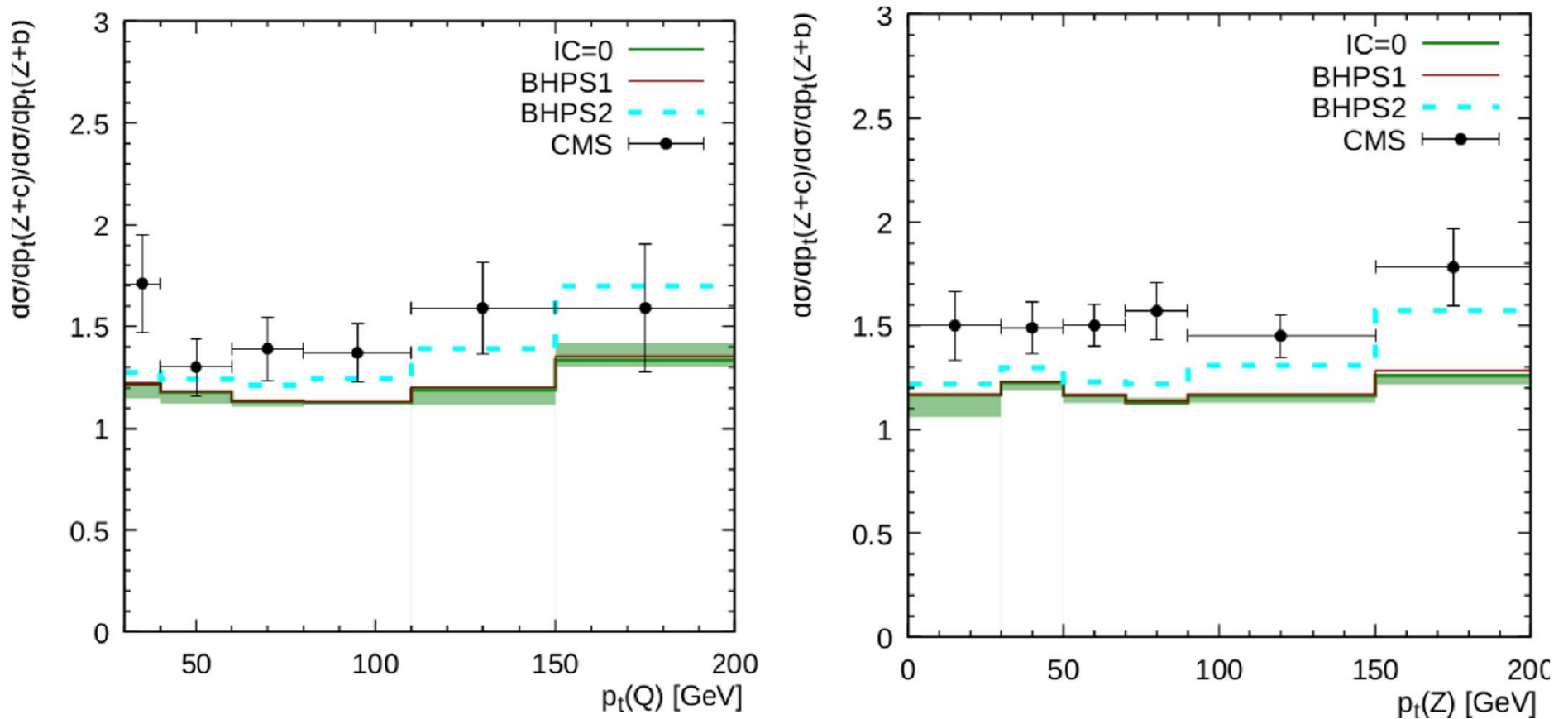
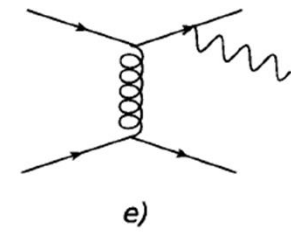
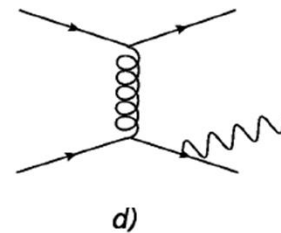
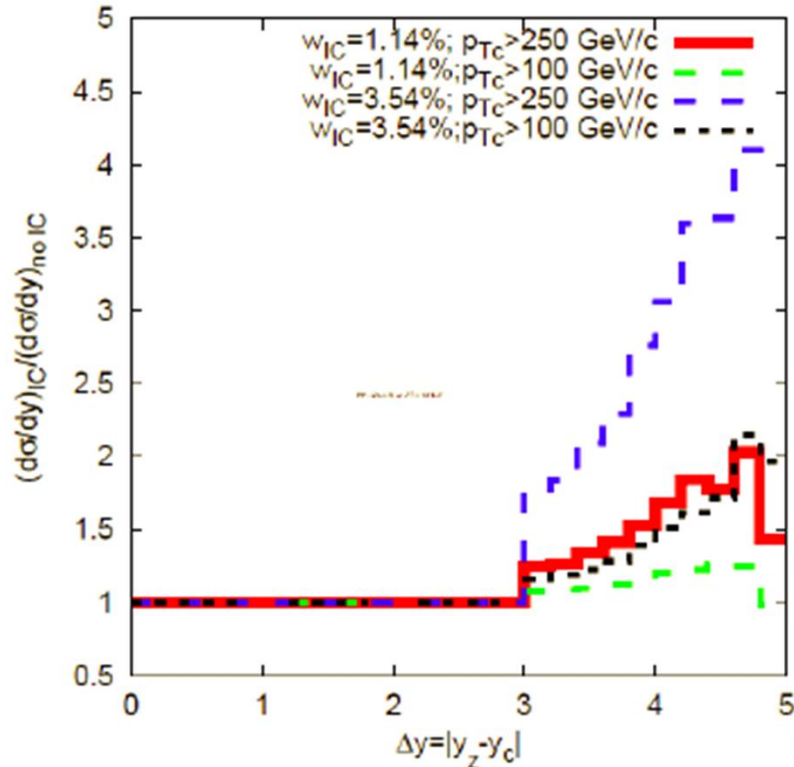


Figure 4: The relative production rate $\sigma(Z + c)/\sigma(Z + b)$ as functions of heavy jet (left panel) and Z boson (right panel) transverse momenta calculated at $\sqrt{s} = 13$ TeV for different IC scenarios with PEGASUS. The experimental data are from CMS [7].

A.V. Lipatov, G.I., M.A. Malyshev, S.M. Turchikhin, Phys.Rev. D 106, 054017 (2022)

PP \rightarrow Z+c+X at $s^{1/2} = 13$ TeV

We suggest the following kinematics: $1.5 < y_c < 2.5$ and $-2.5 < y_Z < -1.5$, i.e., c-jet is produced forward and Z-boson is emitted backward.



The flavour excitation graphs result in a sizable contribution to $d\sigma/dy$ at large Δy .

The ratio of the rapidity distribution with IC contribution to PDF to the one without IC as a function of $\Delta y = |y_Z - y_c|$ at different p_t cuts and IC probabilities $w=1.14\%$ (BHPS1) and $w=3.54\%$ (BHPS2).

$p+p \rightarrow Z+c\text{-jet}+X$ at $s^{1/2} = 13$ TeV

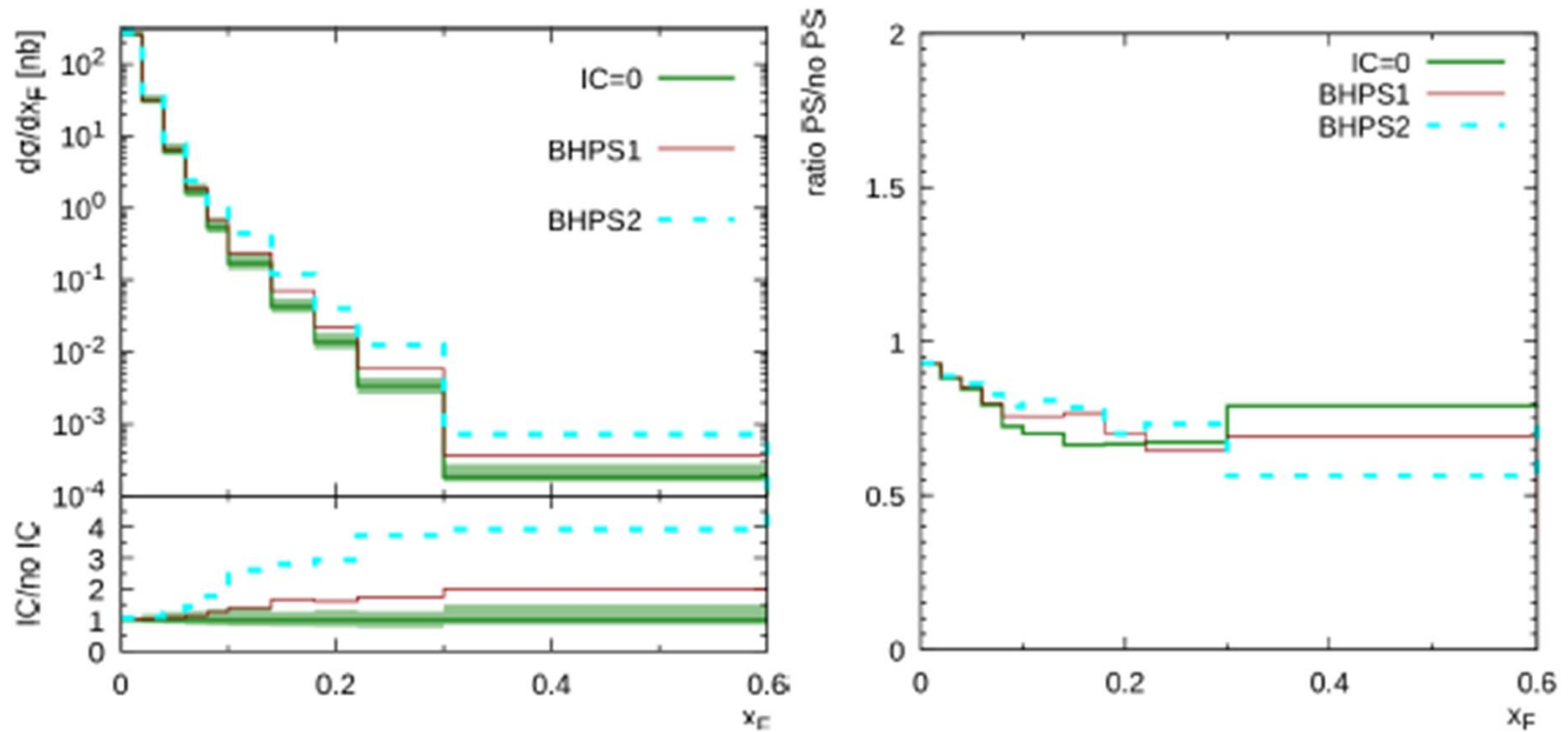


Figure 5: The differential cross sections of associated $Z + c$ production in pp collisions at $\sqrt{s} = 13$ TeV for different intrinsic charm parametrization and their ratios to the zero IC scenario calculated using PEGASUS tool as a function of Feynman variable x_F (left). Right: The ratio of the cross sections calculated with and without PS for the different parametrizations.

A.V. Lipatov, G.I., M.A. Malyshev, S.M. Turchikhin, Phys.Rev. D 106, 054017 (2022)

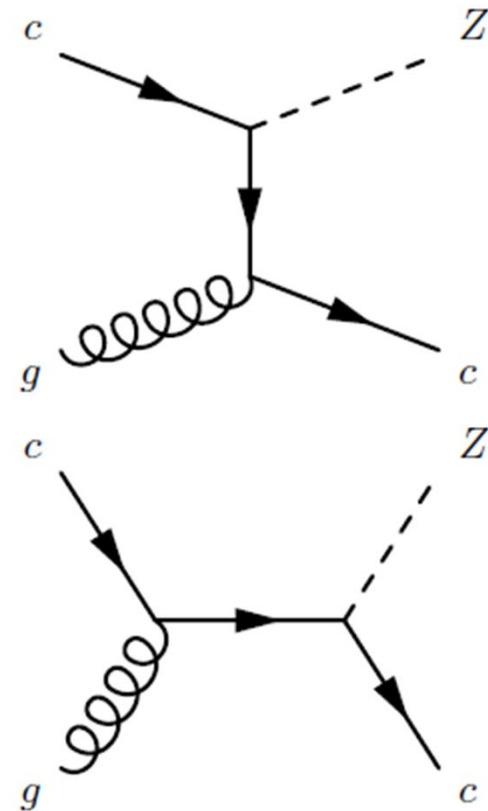
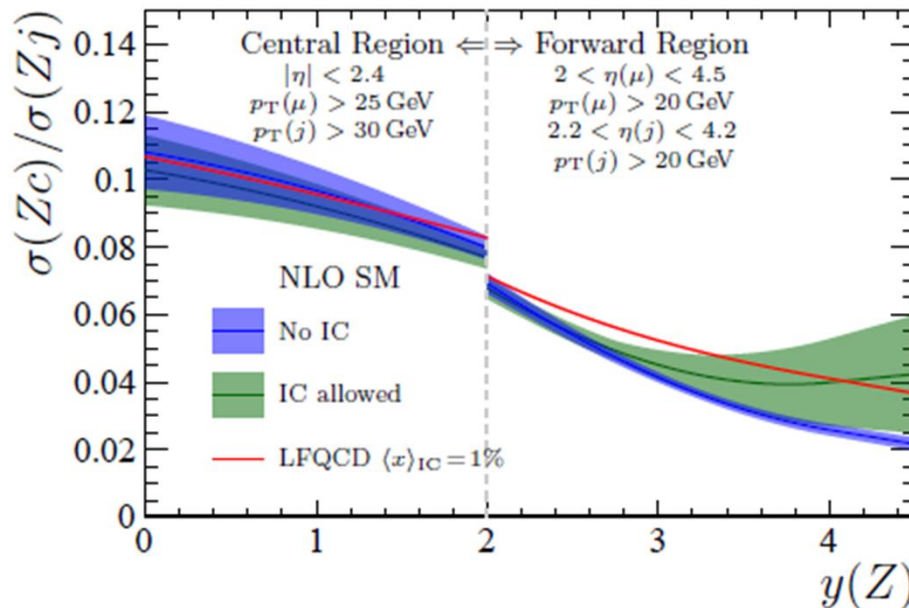
EVIDENCE FOR INTRINSIC CHARM

Intrinsic charm: $Z + c$



LHCb-PAPER-2021-029 NEW!

- ▶ Study production of c -jets in association with a Z
- ▶ Forward region sensitive to high- x , high- Q^2 charm content of the proton



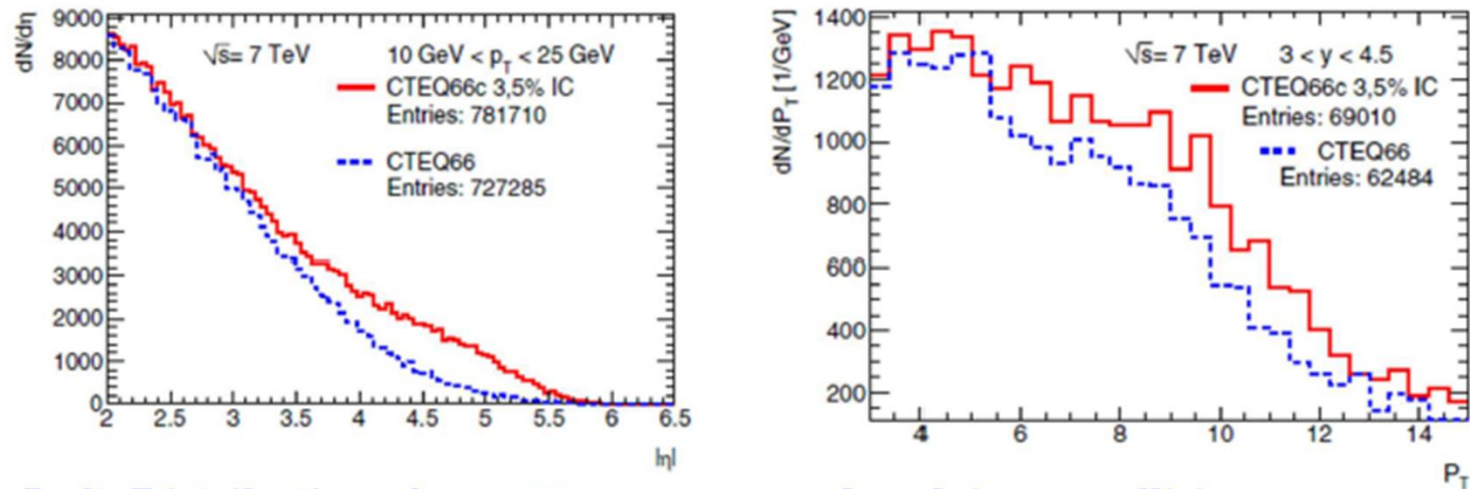
NNPDF fit including the EMC and latest LHCb data results in the local existence of the IC component at the 3σ level at $0.3 < x < 0.6$. The average momentum fraction of IC is about $=0.62 \pm 0.28$ in this x -region.

LHCb Collab., R.Aaij e.a., Phys.Rev.Lett. 128, 08200 (2022).

NNPDF Collab., Nature, 68, 483 (2022); arXiv:2208.08372 v1 [hep-ph]

Our predictions for LHCb on the inclusive production of D-mesons at p-p collision published in G.I. Lykasov, et al., EPL,99 92012) 21002, arXiv:1205.1131.

One can see an enhancement in these observables due to the IC contribution



Left: Distribution of $D_0 + \bar{D}_0$ mesons produced in p-p collision as a function of the pseudo-rapidity $|\eta|$ including the IC component with probability $w=3.5\%$ (red histogram). The blue histogram corresponds to the PDF of type CTEQ66 without the IC.

Right: Transverse momentum distribution of these mesons. Notations are the same as in the left plot.

Next prediction for the LHCb: the measurement of the asymmetry $[\sigma(pp \rightarrow D^+ X) - \sigma(pp \rightarrow D^- X)] / [\sigma(pp \rightarrow D^+ X) + \sigma(pp \rightarrow D^- X)]$ as a function of p_T or y . It can give us information on the charm-anticharm asymmetry by inclusion of the IC component in the proton PDF.

Electro-magnetic form factors within the lattice QCD

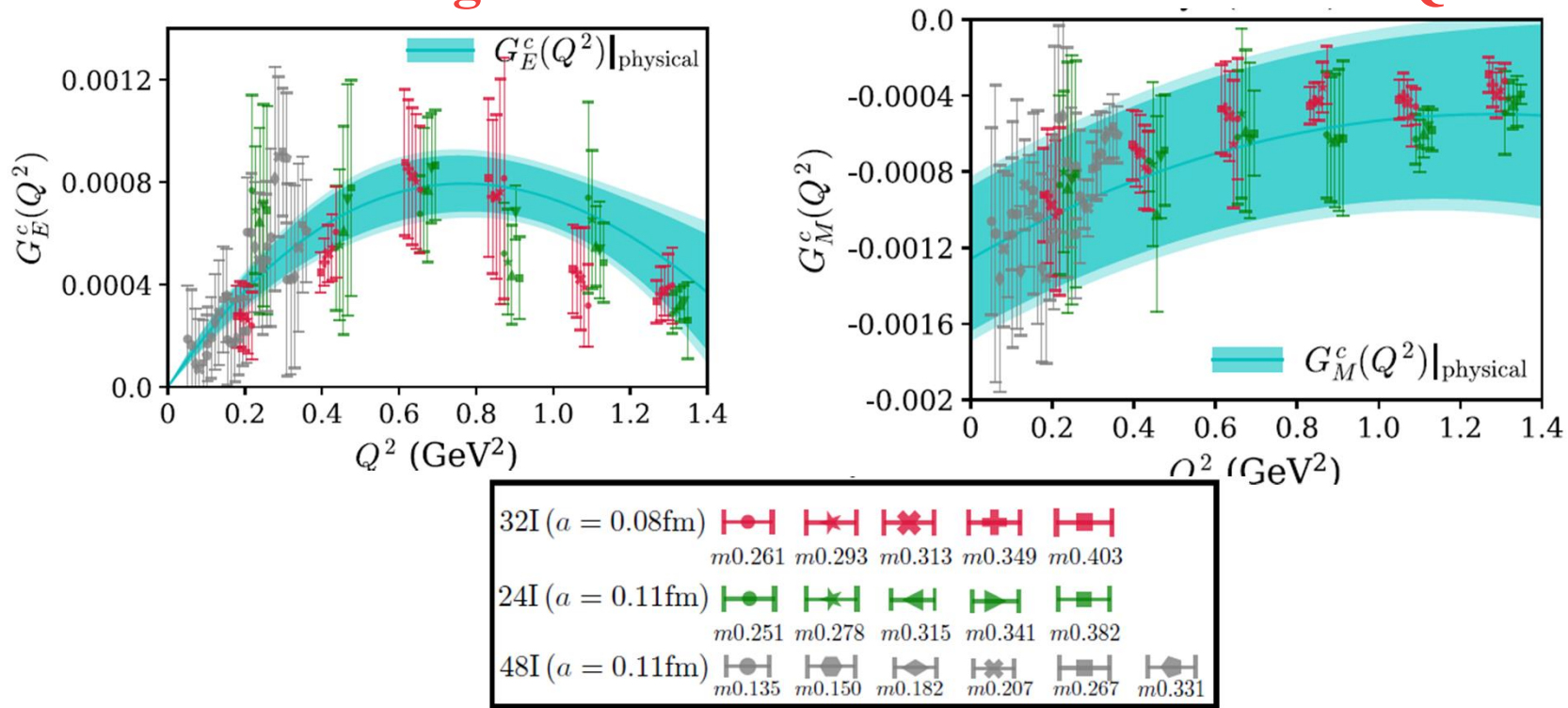


Figure 2: $G_{E,M}^c(Q^2)$ matrix elements obtained from the 48I, 32I, and 24I ensembles. Corresponding legends for different pion masses are included in the lower panel of the figure. The numbers in the legends, such as m_{139} , m_{251} represent the data points corresponding to pion mass 139 MeV and 251 MeV, respectively at different Q^2 -values. The cyan band indicates $G_{E,M}^c(Q^2)|_{\text{physical}}$. The outer (lighter tinted) cyan margins represent an estimate of systematic uncertainty. Matrix elements at the same Q^2 -value but at different pion masses are shown with small offsets for better visibility.

Raza Sabbir Sufian, S. Brodsky, et al., Phys. Lett. B 808 (2020),135633

Non vanishing asymmetric charm-anticharm sea in a nucleon, as the IC confirmation

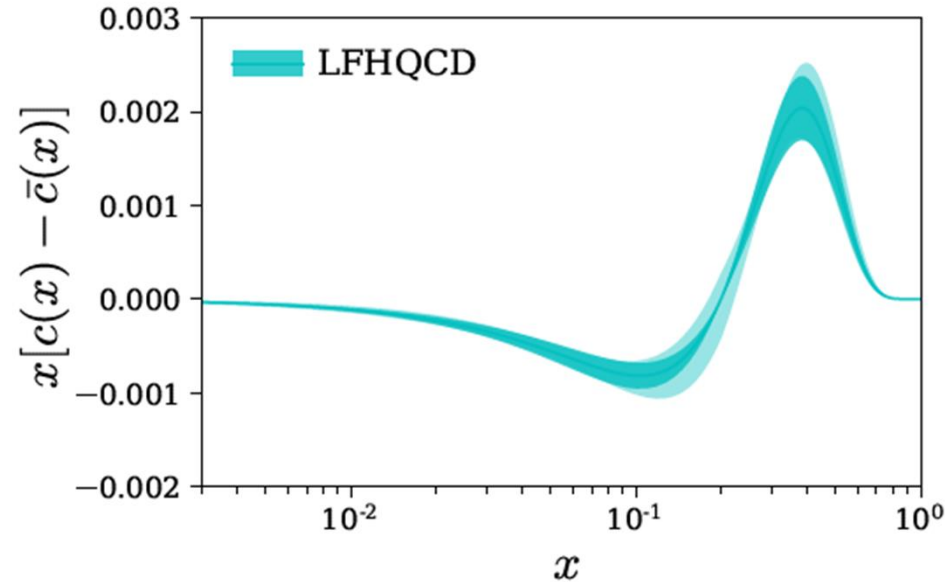


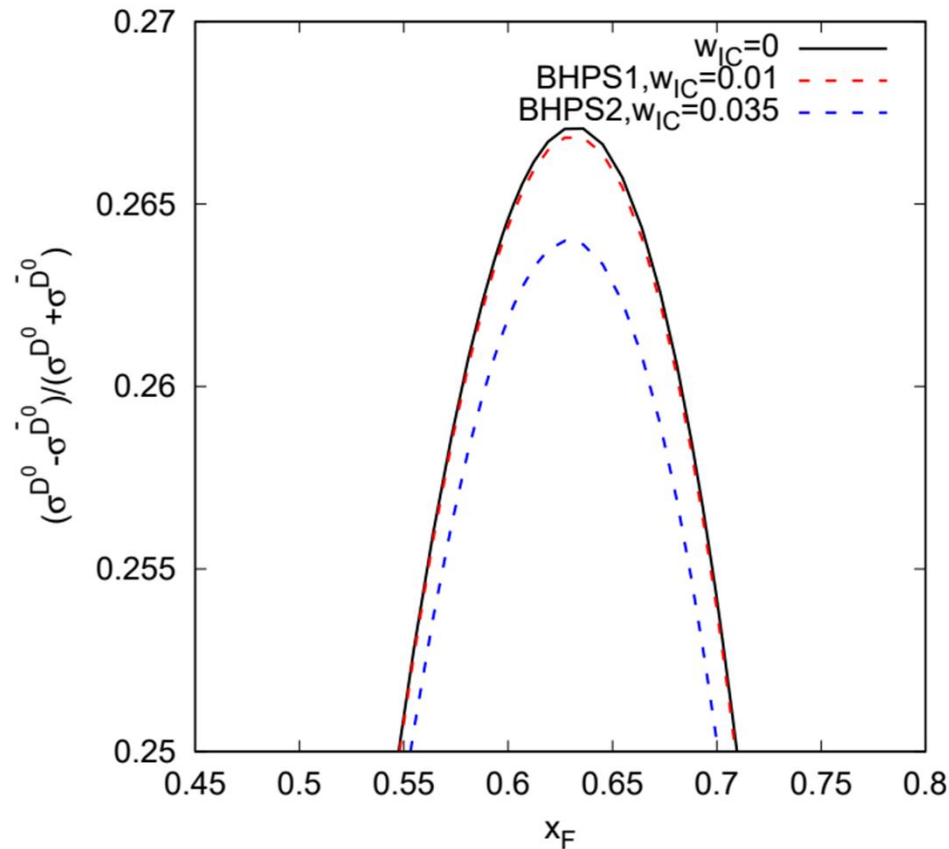
Figure 3: The distribution function $x[c(x) - \bar{c}(x)]$ obtained from the LFHQCD formalism using the lattice QCD input of charm electromagnetic form factors $G_{E,M}^c(Q^2)$. The outer cyan band indicates an estimate of systematic uncertainty in the $x[c(x) - \bar{c}(x)]$ distribution obtained from a variation of the hadron scale κ_c by 5%. It was taken from Ref. [1].

The nonzero

$G_E^c(Q^2)$ indicates the existence of a nonvanishing asymmetric charm-anticharm sea in the nucleon. Performing a non-perturbative analysis based on holographic QCD and the generalized Veneziano model, we study the constraints on the $[c(x) - \bar{c}(x)]$ distribution from the lattice QCD results presented here. Our results provide complementary information and motivation for more detailed studies of physical observables that are sensitive to intrinsic charm and for future global analyses of parton distributions including asymmetric charm-anticharm distribution.

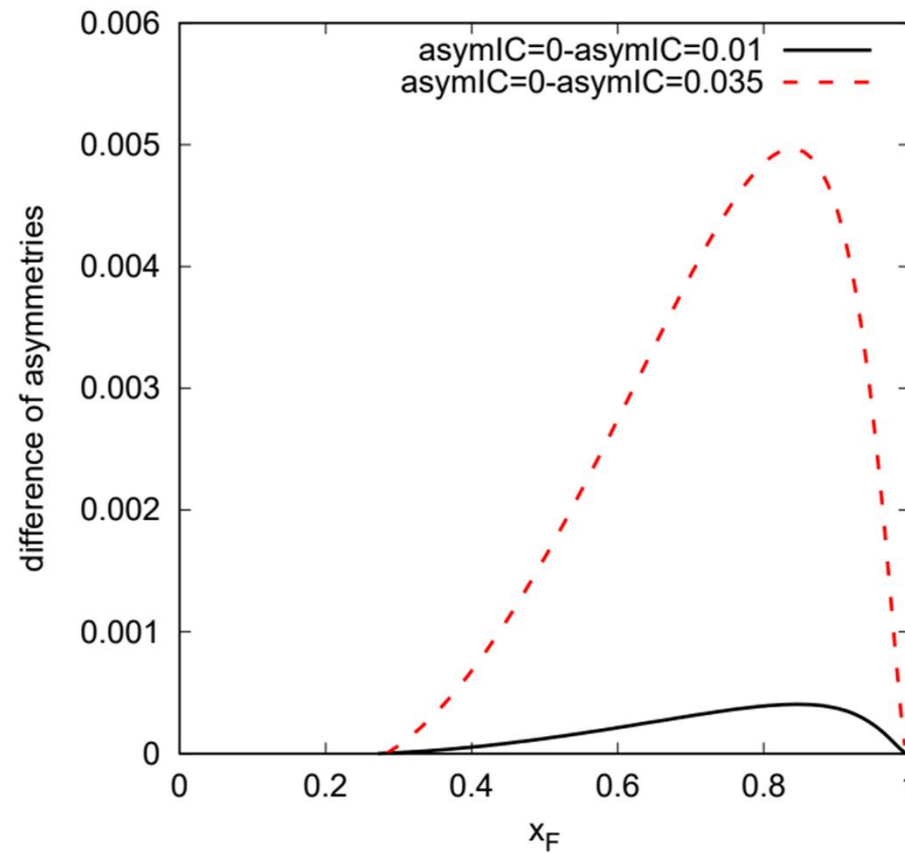
Raza Sabbir Sufian, S. Brodsky, et al., Phys. Lett. B 808 (2020),135633

D-meson production in p-p collisions at the initial energy about 400 GeV in the l.s.



Our predictions on the distribution of the D-anti D asymmetry as a function of the Feynman variable at different IC probabilities.

D-meson production in p-p collisions at the initial energy about 400 GeV in the Ls.



The difference between D-Dbar asymmetry at the non zero **IC** and at **IC=0**

SUMMARY

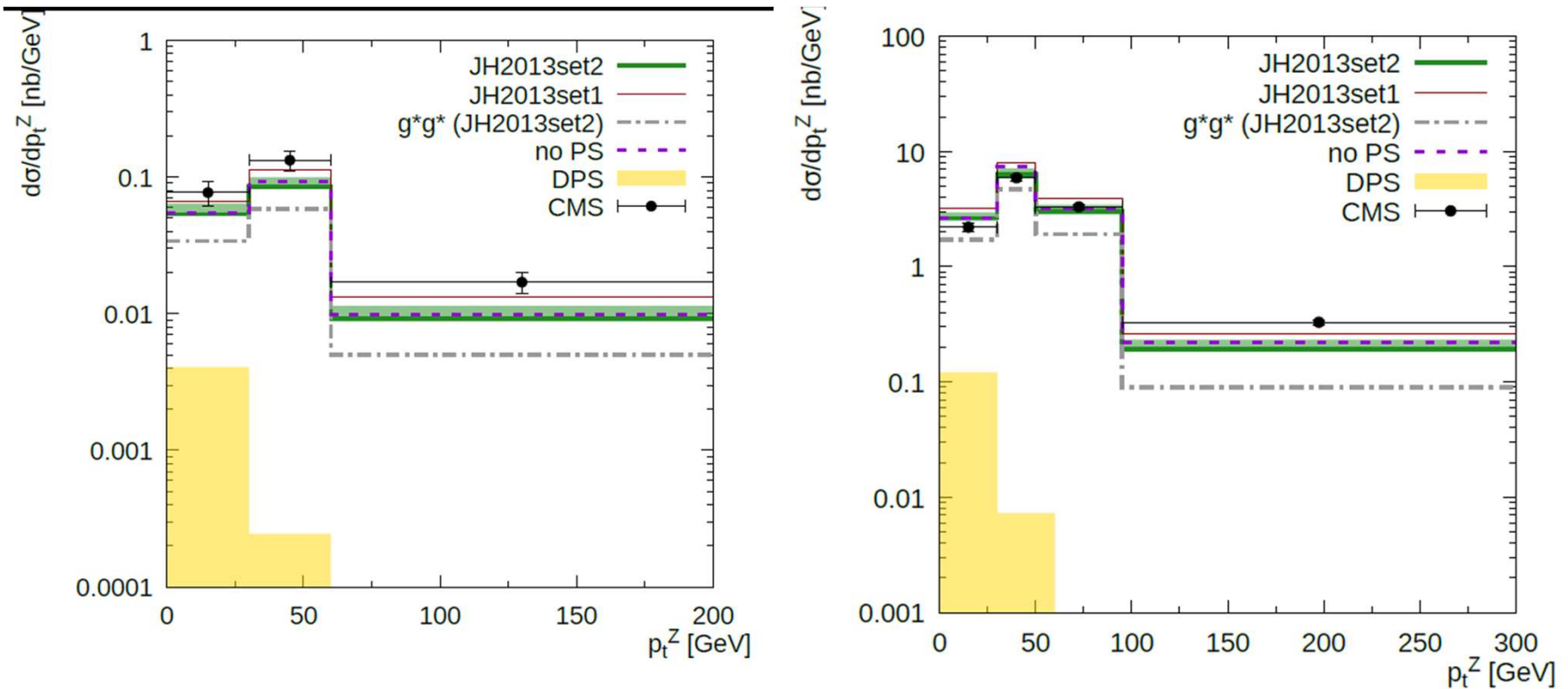
1. The lattice QCD calculation shows that the charm quark contribution to the electric form factor of proton doesn't vanish. It leads to the non vanishing asymmetry $c(x) - \bar{c}(x)$, which can indicate the **IC existence in nucleon**.
2. We illustrate that the back-to back production of c-jet and Z-boson in pp results in a sizable enhancement in p_t - spectra, about 200%-300% , when the **IC** component in PDF is taken into account.
3. We predict the big enhancement in the x_F -spectrum of c-jet produced in $p+p \rightarrow Z+c+X$ about 40%-100% at $x_F > 0.1$, when the **IC** component in PDF is included.
4. The inclusive spectrum of D-mesons produced in p-p collisions at the LHC energy as a function of the pseudo-rapidity $|\eta|$ or transverse momentum p_T can have an enhancement at $3.5 < |\eta| < 5$ and $10 < p_T < 25$ GeV/c, if the **IC** contribution is included.
5. The measurement of $(\sigma(D^+) - \sigma(D^-)) / (\sigma(D^+) + \sigma(D^-))$ as a function of x_F is very promising for the search of the charm-anticharm quarks asymmetry, which could be very good confirmation of the existence of the **IC** component in nucleon.

**THANK YOU VERY MUCH FOR
YOUR ATTENTION !**

BACK UP

p+p -> Z+c-jet+X at $s^{1/2} = 8 \text{ TeV} \ \& \ 13 \text{ TeV}$

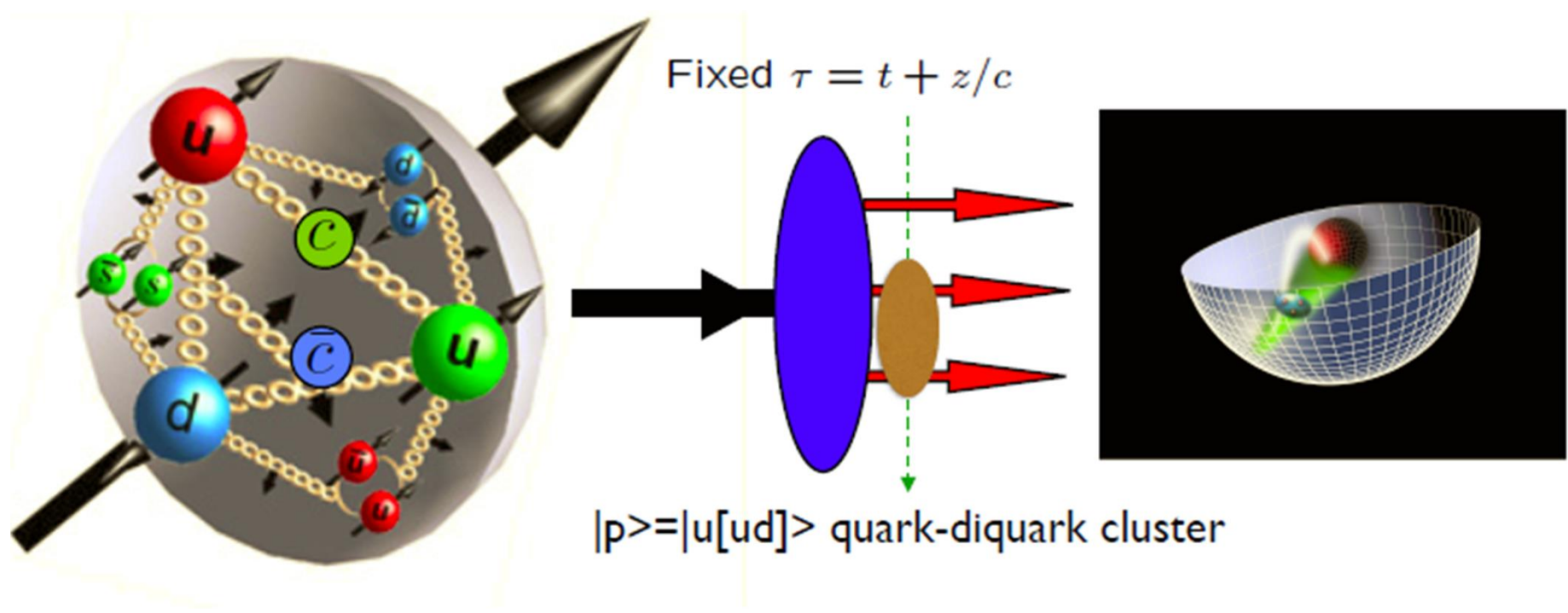
CMS data



Left: the Z-boson distribution as a function of its transverse momentum p_t^Z at $s^{1/2} = 8 \text{ TeV}$ and different TMD gluon density functions; PS means the parton shower; DPS is the double parton scattering.

Right: the same as at left but at $s^{1/2} = 13 \text{ TeV}$.

BHPS model: S.J. Brodsky, P. Hoyer, C. Peterson and N. Sakai, Phys.Lett.B9(1980) 451; S.J. Brodsky, S.J. Peterson and N. Sakai, Phys.Rev. D23 (1981) 2745.



S.J. Brodsky

with P. Hoyer, N. Sakai, C. Peterson, A. Mueller, J. Collins, S. Ellis, J. Gunlon,

Daniel Craik
on behalf of the LHCb collaboration

Massachusetts Institute of Technology

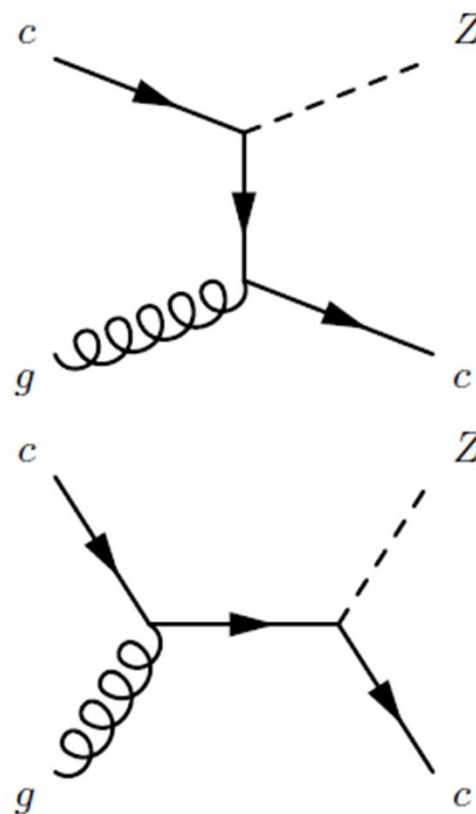
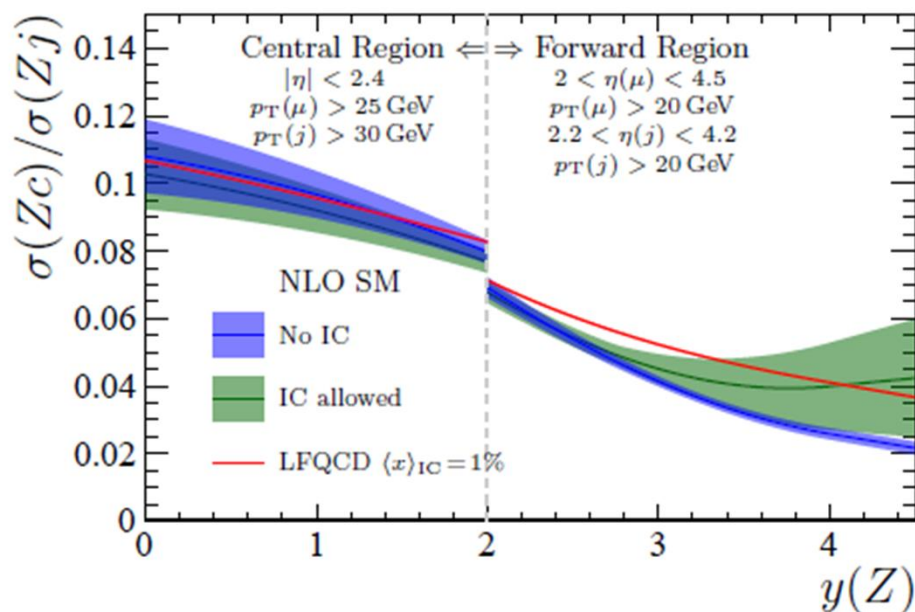
4th August, 2021

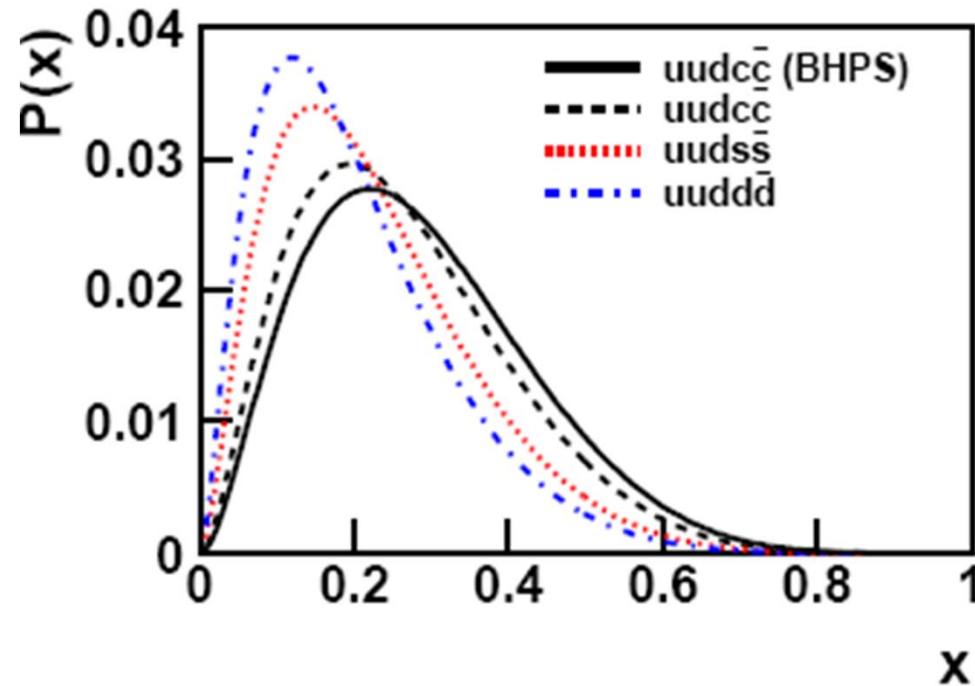
Intrinsic charm: $Z + c$



LHCb-PAPER-2021-029 NEW!

- ▶ Study production of c -jets in association with a Z
- ▶ Forward region sensitive to high- x , high- Q^2 charm content of the proton





The x -distribution of the intrinsic Q calculated within the BHPS model. **There is an enhancement at $x > 0.1$**
 Jen-Chieh Peng & We-Chen Chang, hep-ph/1207.2193.

INTRINSIC HEAVY QUARK DISTRIBUTION IN PROTON

Integrating $P(x_1, \dots, x_5)$ over $dx_1 \dots dx_4$ and neglecting of all quark masses except the charm quark mass, we get

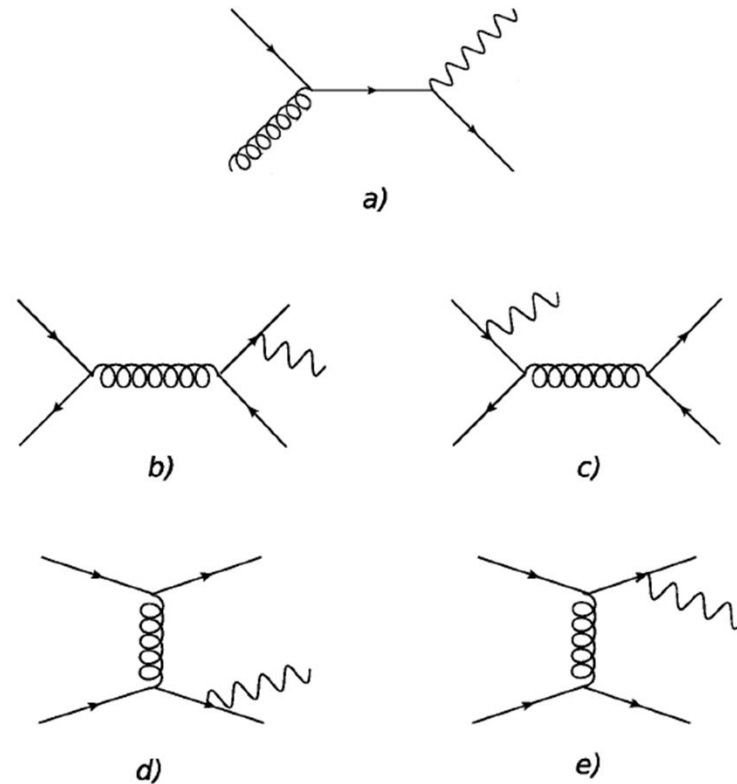
$$P(x_5) = \frac{1}{2} \bar{N}_5 x_5^2 \left[\frac{1}{3} (1 - x_5)(1 + 10x_5 + x_5^2) + 2x_5(1 + x_5) \ln(1 - x_5) \right]$$

Where $\bar{N}_5 = N_5 / m_{4,5}^4$, N_5 is the normalization constant. Here $m_4 = m_5 = m_c = m_c$ is the bar mass of the charmed quark. W_{IQ} determines some probability to find the Fock state $|uudQQ\rangle$ in the proton.

One can see qualitatively that $P(x_5)$ vanishes at $x_5 \rightarrow 0$ and $x_5 \rightarrow 1$ and has an enhancement at $0 < x_5 < 1$

$$xc(x, \mu_0^2) = xc_{\text{ext}}(x, \mu_0^2) + xc_{\text{int}}(x, \mu_0^2).$$

S.J.Brodsky, V.A.Bednyakov, G.L., J.Smiesko, S.Tokar, Progr.Part.Phys. 93, 108 (2017)



^TThe $\mathcal{O}(\alpha\alpha_s)$ (a) and $\mathcal{O}(\alpha\alpha_s^2)$ (b) – (e) contributions to the $\gamma(Z) + Q$ production.

a)QCD compton; b),c) QQ annihilaton; d),e) flavour excitation

S.J.Brodsky, V.A.Bednyakov, G.L., J.Smiesko, S.Tokar, Progr.Part.Phys. v.93, 108 (2017)

S.J.Brodsky, G.L., A.V.Lipatov, J.Smiesko, Progr.Part.Phys. v.114, 103802 (2020)

PHOTON (DI-LEPTON) AND c(b)-JETS PRODUCTION IN P-P

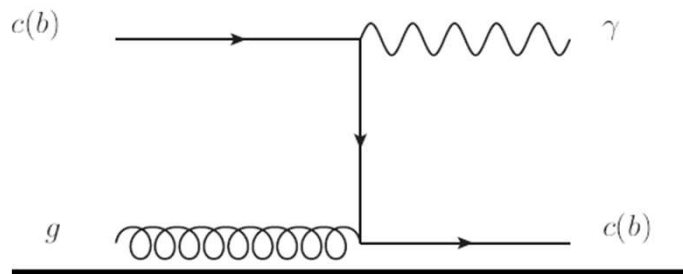


Fig.a. Feynman diagram for the process $c(b)+g \rightarrow \gamma+c(b)$

$$x_F = \frac{2p_T}{S^{1/2}} \text{sh}(\eta); p_{TV} = -p_{Tc}.$$

for Fig.a

$$x_c \geq x_F > 0.1$$

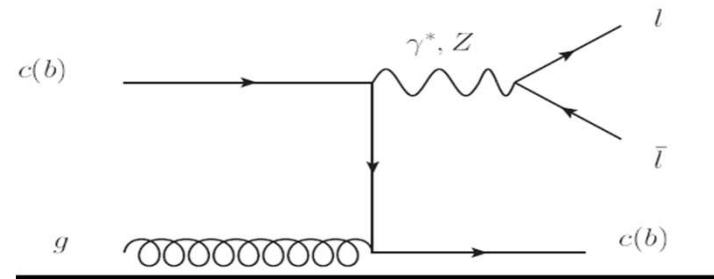


Fig.b. Feynman graph for the process $c(b)+g \rightarrow \gamma/Z^0+c(b)$

$$x_{c(b)} = \frac{m_{l^+l^-}^2}{x_g S} + x_{c(b)}^f$$

for Fig.b

$$x_{c(b)} = \frac{m_{l^+l^-}^2}{x_g S} + x_{c(b)}^f > 0.1$$

PRODUCTION OF HEAVY FLAVOURS IN HARD P-P COLLISIONS

$$E \frac{d\sigma}{d^3p} = \sum_{i,j} \int d^2k_{iT} \int d^2k_{jT} \int_{x_i^{\min}}^1 dx_i \int_{x_j^{\min}}^1 dx_j f_i(x_i, k_{iT}) f_j(x_j, k_{jT}) \frac{d\sigma_{ij}(\hat{s}, \hat{t})}{d\hat{t}} \frac{D_{i,j}^h(z_h)}{\pi z_h}$$

$$x_i^{\min} = \frac{x_T \cot(\frac{\theta}{2})}{2 - x_T \tan(\frac{\theta}{2})} \quad x_F \equiv \frac{2p_z}{\sqrt{s}} = \frac{2p_T}{\sqrt{s}} \frac{1}{\tan \theta} = \frac{2p_T}{\sqrt{s}} \sinh(\eta)$$

$$x_i^{\min} = \frac{x_R + x_F}{2 - (x_R - x_F)} \quad x_R = 2p/\sqrt{s}$$

One can see that $x_i \geq x_F$. If $x_F > 0.1$ then, $x_i > 0.1$ and the **conventional sea** heavy quark (extrinsic) contributions are suppressed in comparison to the **intrinsic** ones.

x_F is related to p_T and η . So, at certain values of these variables, in fact, there is **no conventional sea** heavy quark (**extrinsic**) contribution. And we can study the **IQ contributions** in hard processes at the **certain** kinematical region.